Neutrino Emission from Nearby Supernova Progenitors

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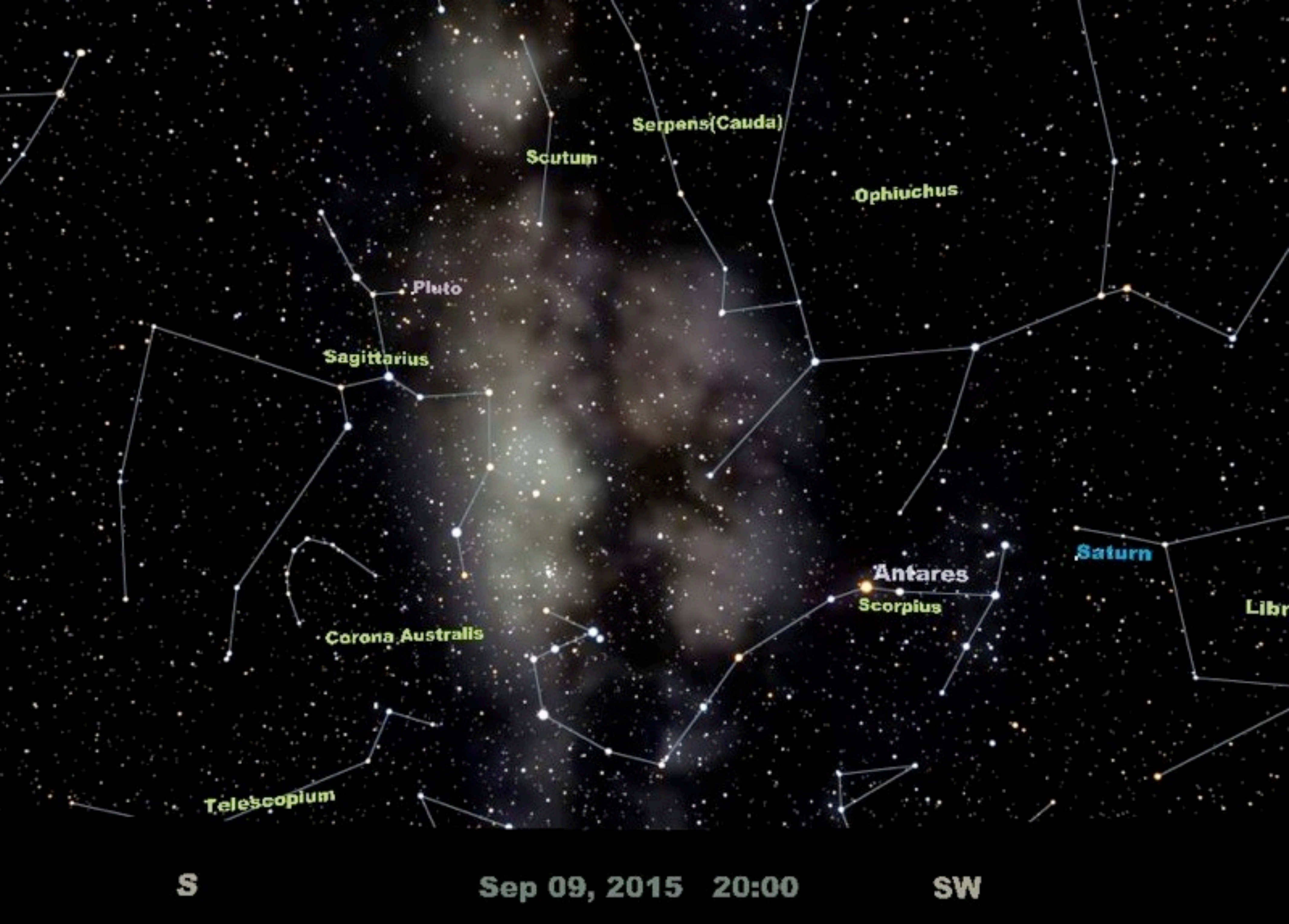

Serpens(Cauda)
Scutum
Ophiuchus
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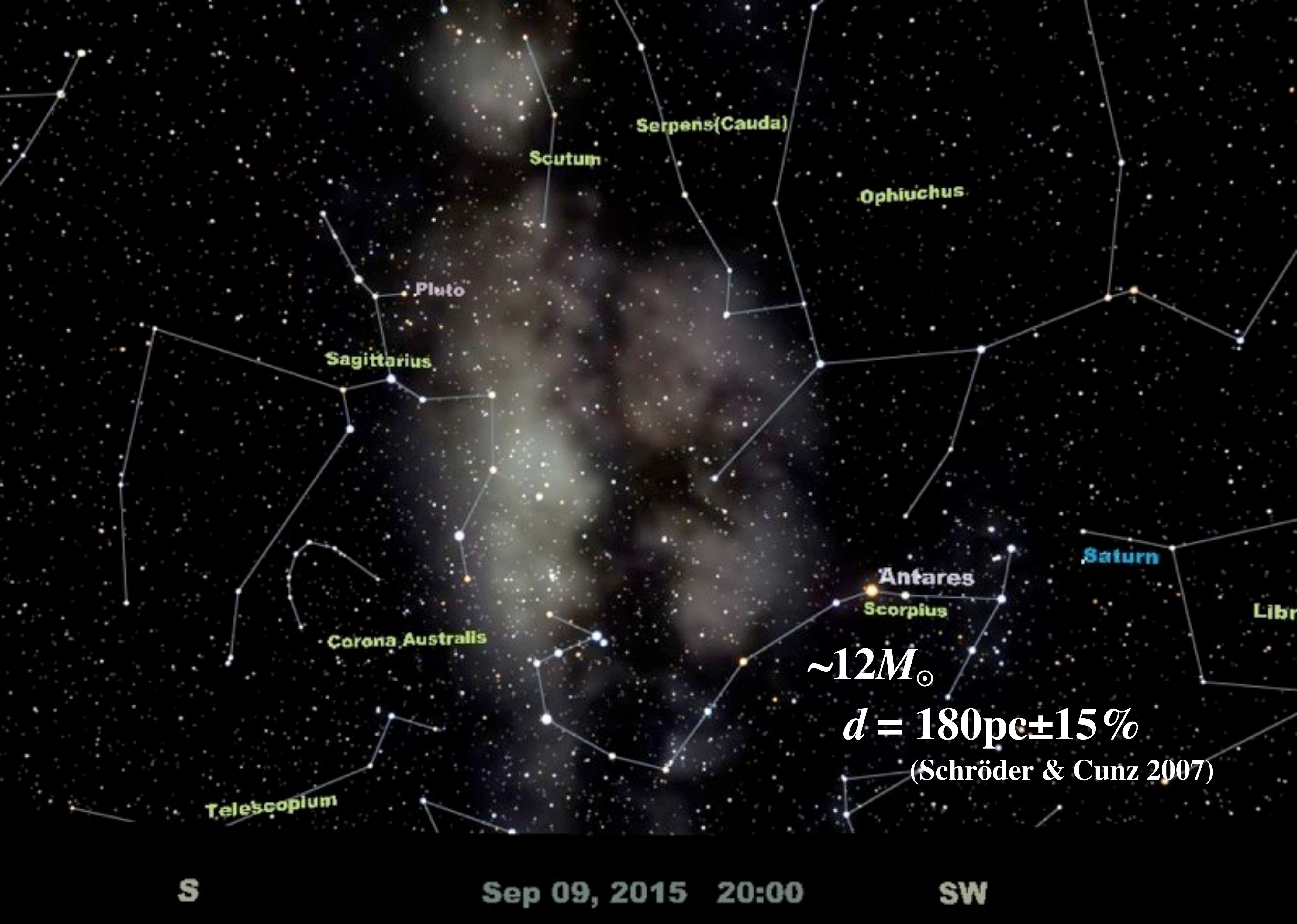
Serpens(Cauda)
Scutum
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Sagittarius
Saturn
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$\sim 12M_\odot$
d = 180pc±15%
(Schröder & Cunz 2007)
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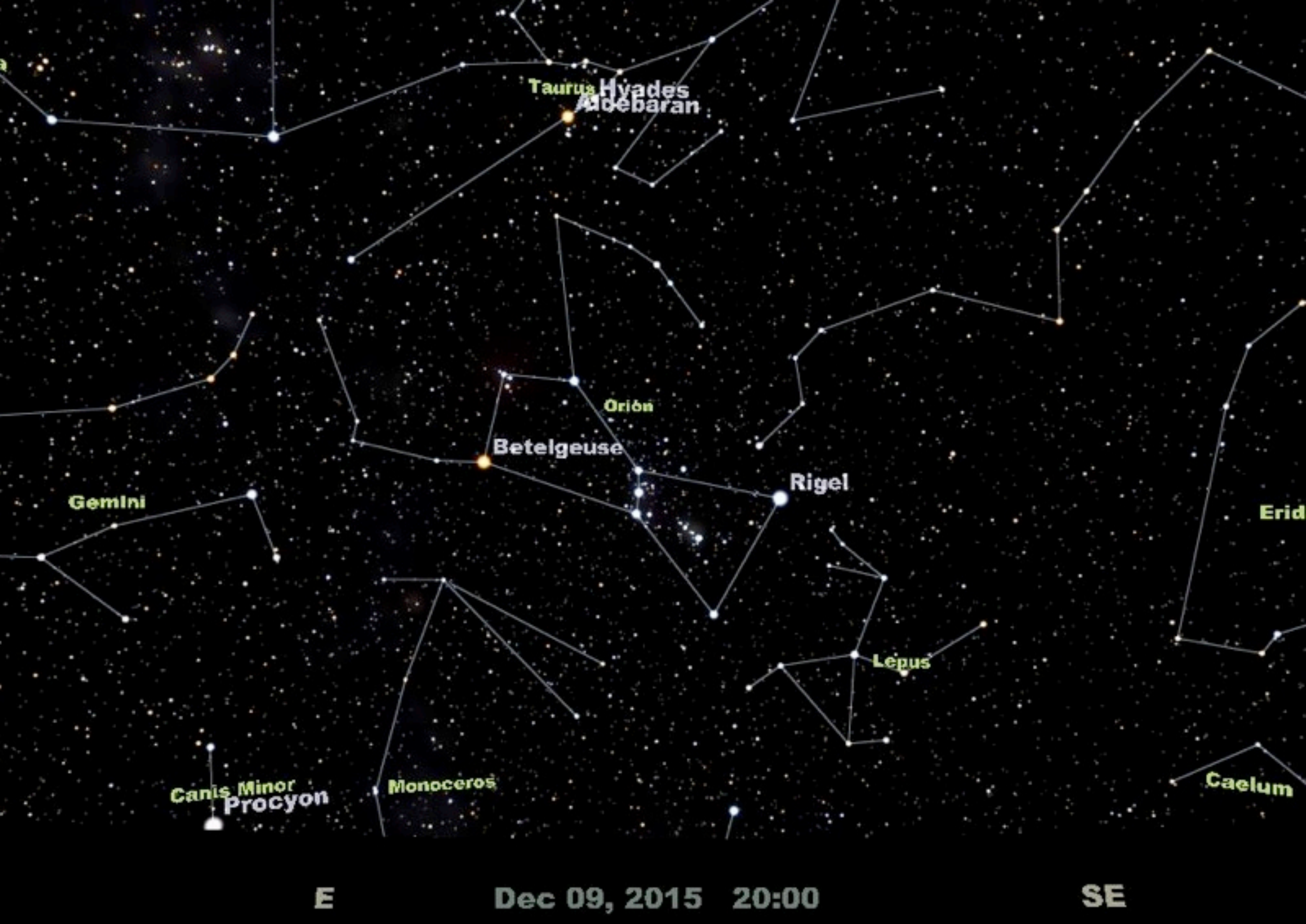
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Hyades
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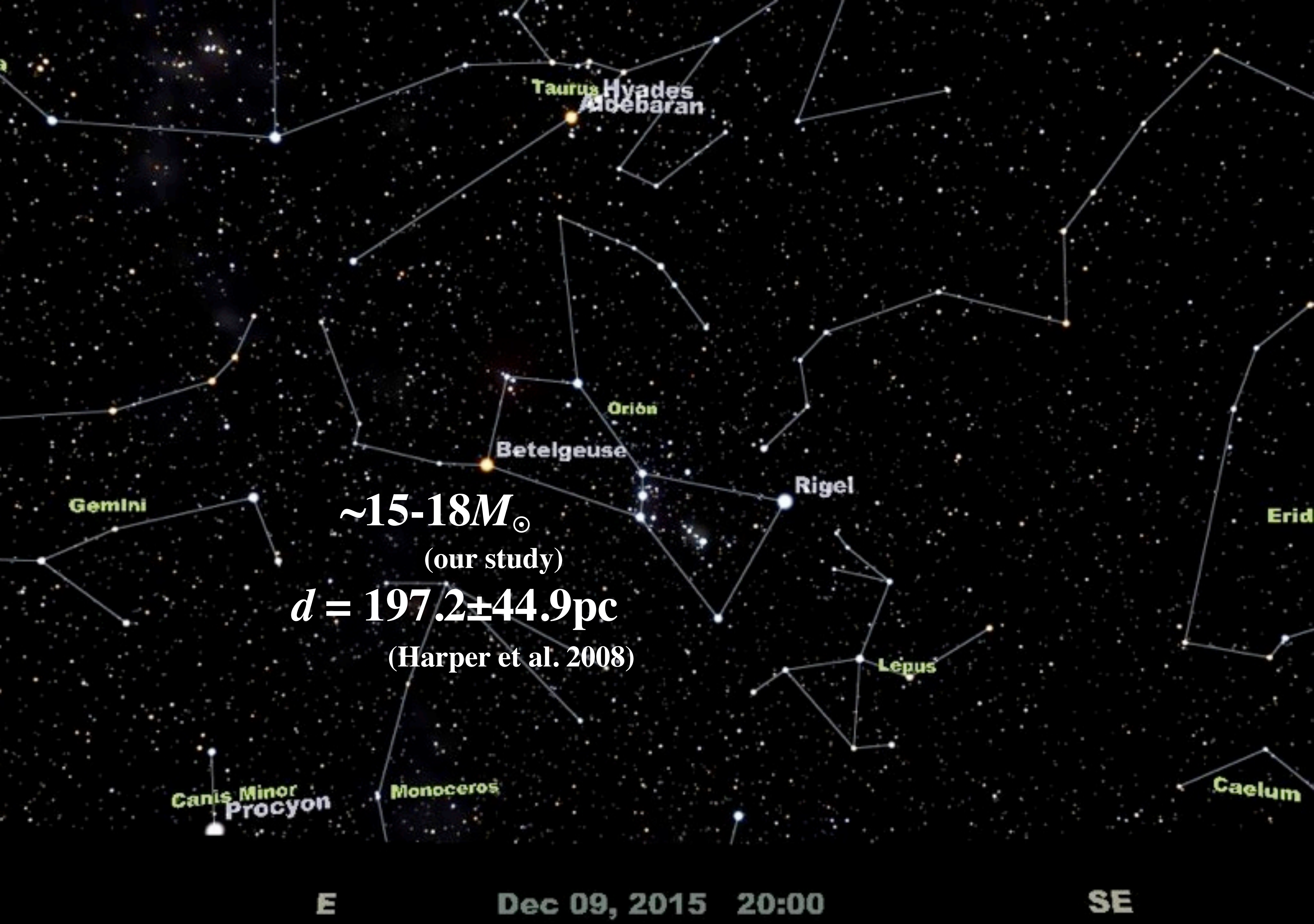
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Caelum
~15-18$M_\odot$
(our study)
d = 197.2±44.9pc
(Harper et al. 2008)
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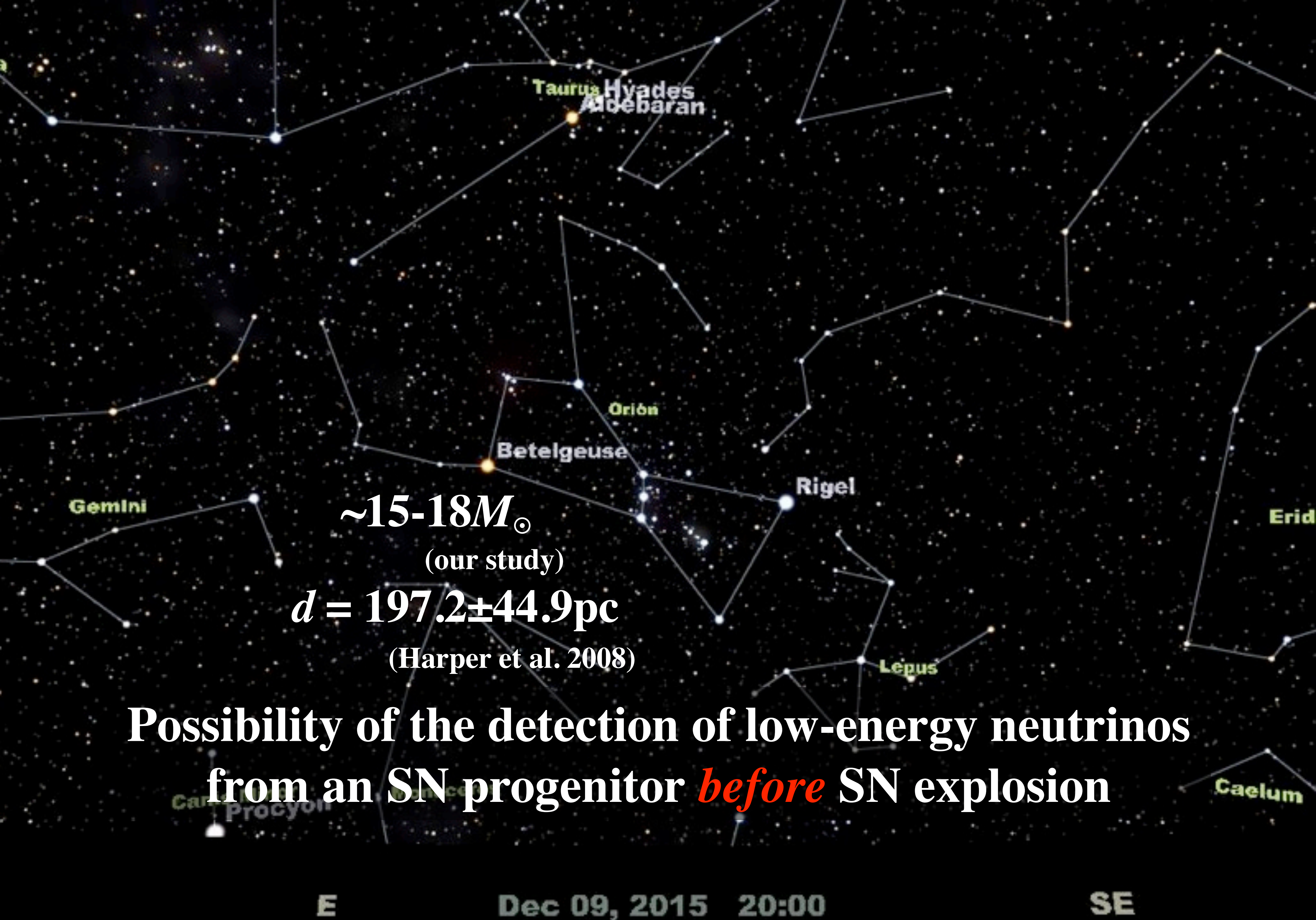


$\sim$15-18$M_\odot$

(our study)

d = 197.2±44.9pc

(Harper et al. 2008)

Possibility of the detection of low-energy neutrinos from an SN progenitor *before* SN explosion

Neutrino Emission during Si-Burning

- Neutrino spectra after C-burning
  - Pair neutrinos (Odrzywolek et al. 2004; Misiaszek et al. 2006)
  - Plasma neutrinos (Odrzywolek 2007)
  - Weak interaction in Fe core (Odrzywolek 2009)
- Event numbers of an SN progenitor by KamLAND, SK, GAZOOKS, Borexino (Odrzywolek et al. 2007)
- Neutrino emission from a progenitor of an electron-capture SN: comparison with neutrino emission from core-collapse SNe (Kato et al. 2015, ApJ 808, 168)

We investigate neutrino emission of 12, 15, and 20$M_{\odot}$ stars during Si-burning.

Estimation of Neutrino Spectra

- **Evolution of massive stars until core-collapse (log $T_C \sim 9.8$)**

(Yoshida & Umeda 2011; Umeda, Yoshida, Takahashi 2012; Takahashi, Yoshida, Umeda 2013; Yoshida, Okita, Umeda 2014; Takahashi, Umeda, Yoshida 2014; Takahashi et al. 2015)

→ **12, 15, and 20 $M_\odot$ models**

updated from Kato et al. (2015)

- **Rate of neutrino emission by electron pair annihilations**

$$r(\varepsilon_\nu, \varepsilon_{\bar{\nu}}) = \frac{c}{16(2\pi)^{12}\hbar^{12}} \int f_{e-} f_{e+} (2\pi)^4 \delta^4(p_{e-}+p_{e+}-p_\nu-p_{\bar{\nu}}) \frac{|M|^2}{\varepsilon_{e-}\varepsilon_{e+}\varepsilon_\nu\varepsilon_{\bar{\nu}}} d^3p_{e-} d^3p_{e+} d\Omega_\nu d\Omega_{\bar{\nu}}$$

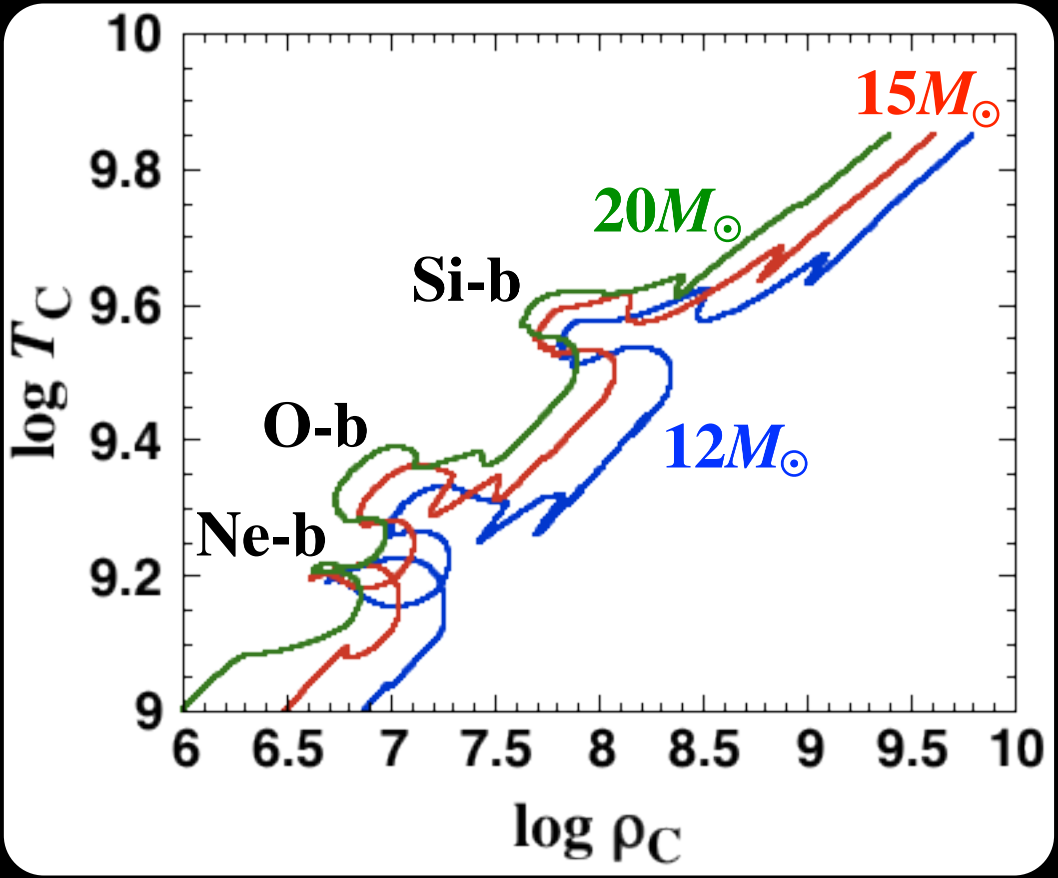
$$|M|^2 = 16 G_F^2 (\hbar c)^2 \{(C_A - C_V)^2 (p_{e-} \cdot p_\nu)(p_{e+} \cdot p_{\bar{\nu}}) + (C_A + C_V)^2 (p_{e+} \cdot p_\nu)(p_{e-} \cdot p_{\bar{\nu}}) + m_e^2 c^4 (C_A^2 - C_V^2)(p_\nu \cdot p_{\bar{\nu}})\}$$

(e.g., Dicus 1972; Yakovlev et al. 2001)

- **Table of ν spectra as functions of T and ρY_e**

→ **Evaluation of ν spectra emitted from each mass mesh of a star**

Advanced Evolution of Massive Stars



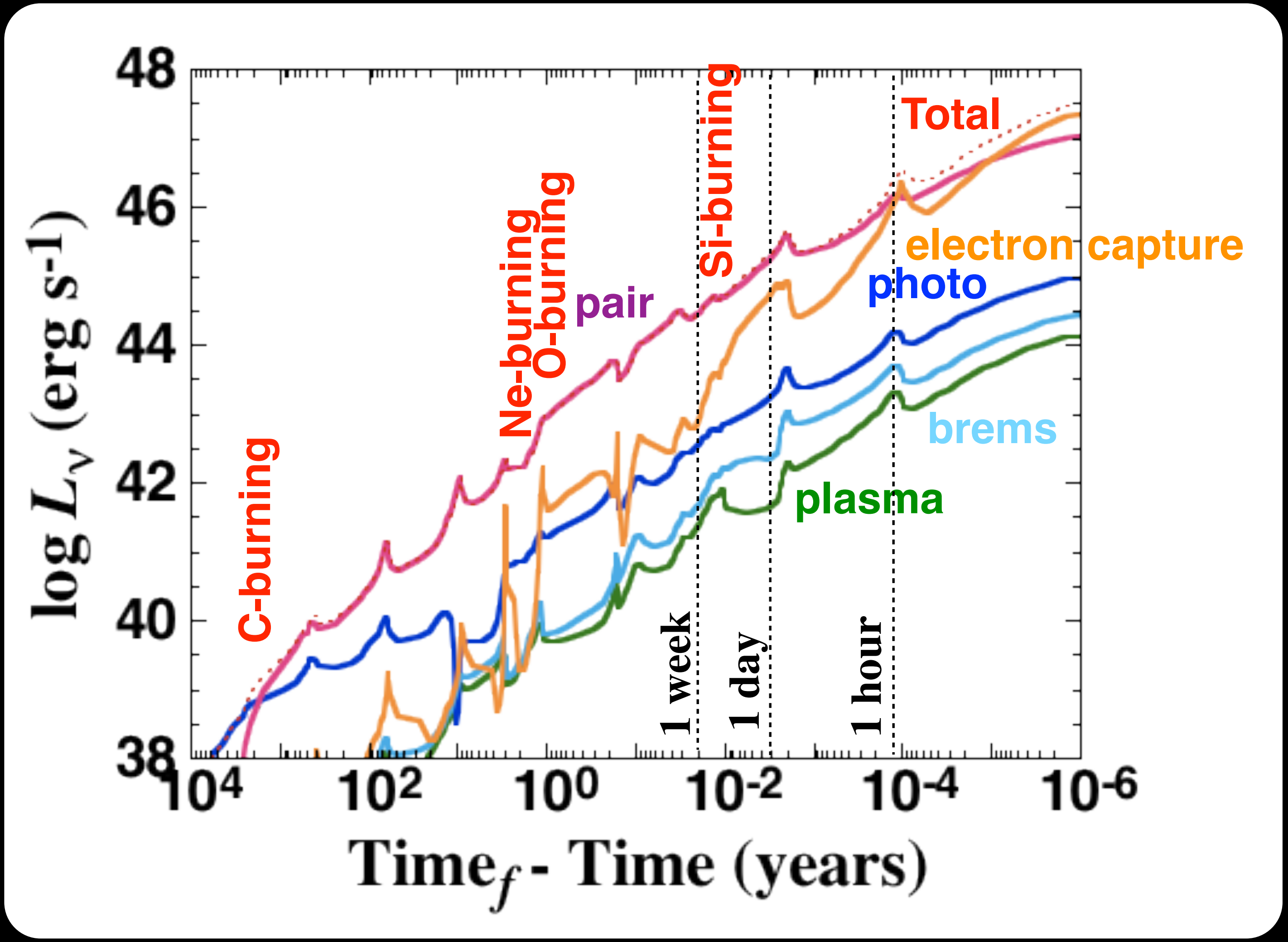
progenitor models

$M/M_\odot$	M_f	M_{CO}	M_{Fe}	$t_{Si\text{-}b}$ (d)
12	10.6	1.82	1.28	8.6
15	12.3	2.74	1.49	4.4
20	14.3	4.64	1.44	1.1

- **Period of Si-burning depends on stellar mass.**
- **Observation of neutrinos from an SN progenitor**
  → **Information of the innermost region of the star**

Neutrino Luminosity

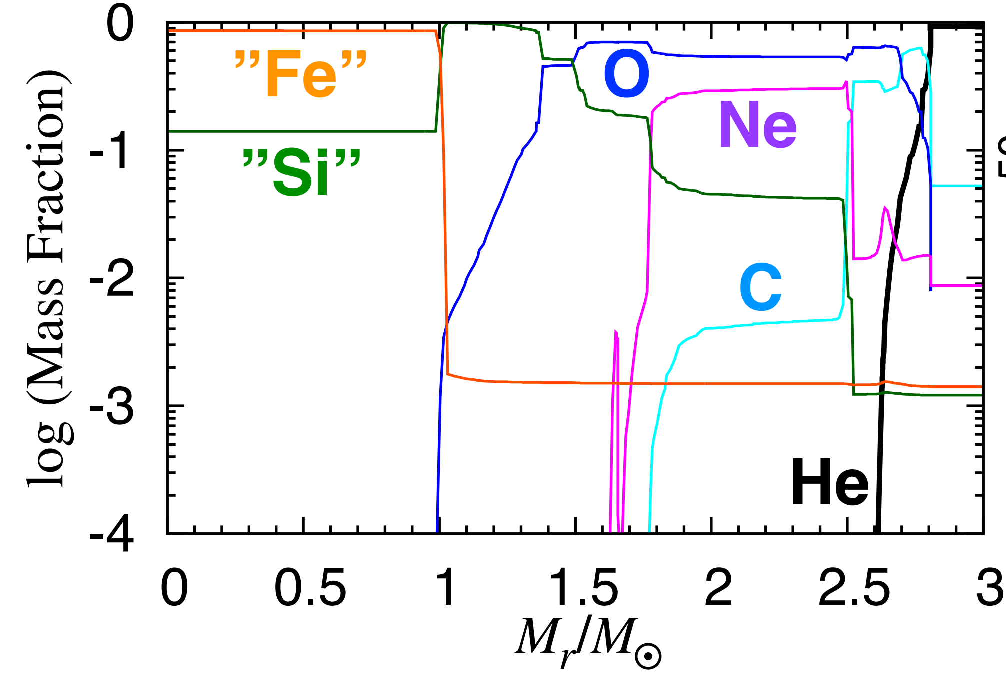
15 $M_\odot$ star

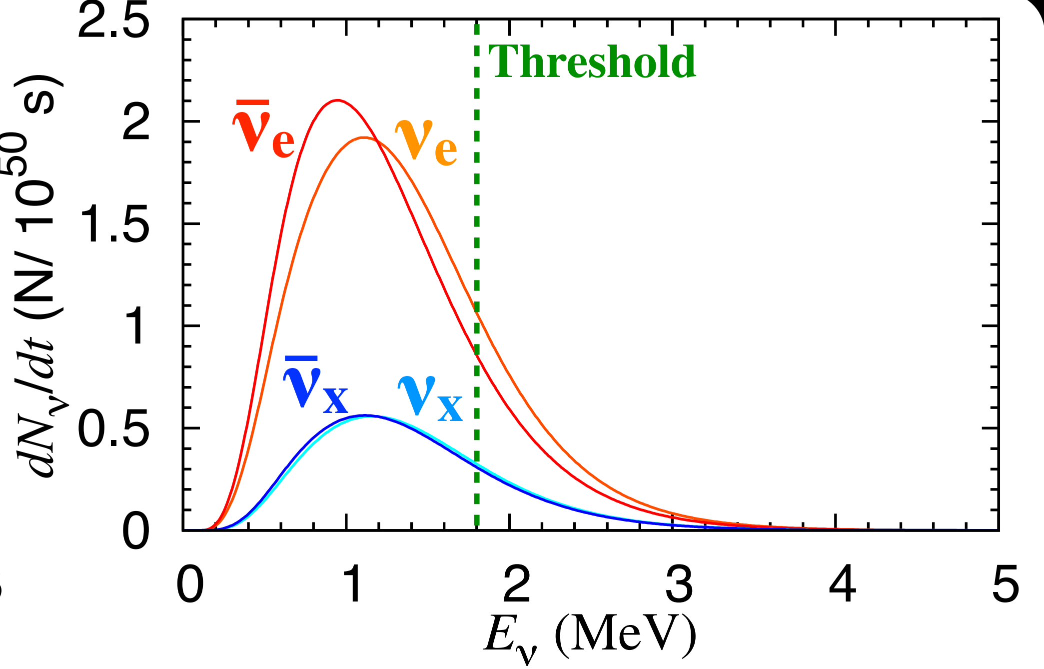


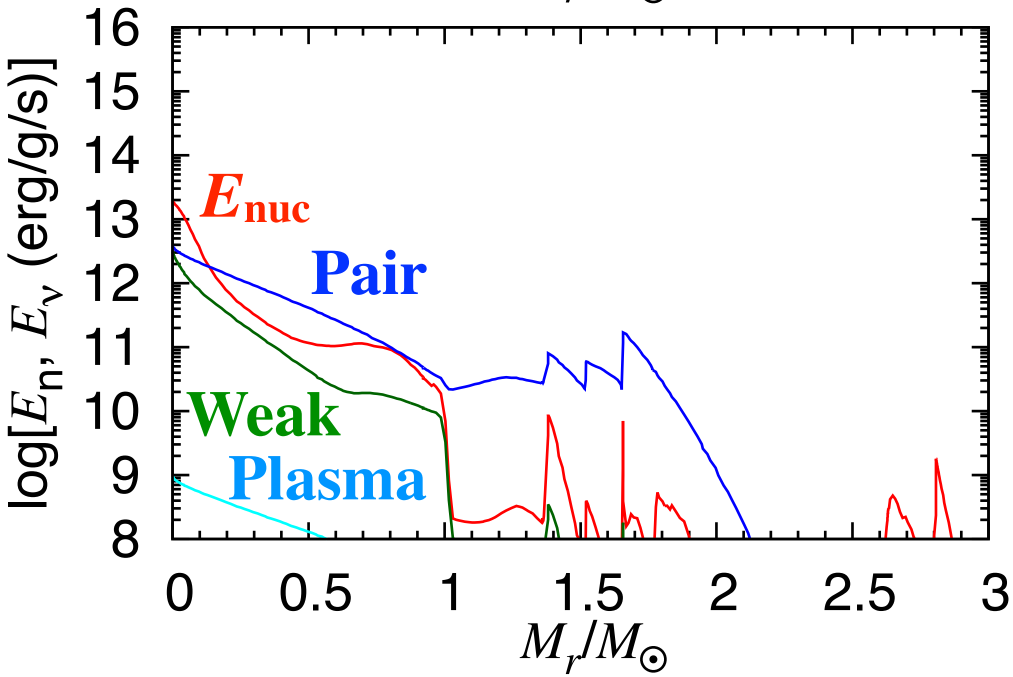
- **Neutrinos are mainly emitted by pair-annihilation of e^--e^+.**

  ➡ **$L_\nu \sim 10^{45\text{-}47}$ erg/s during Si-burning**

Neutrinos in Si-Burning





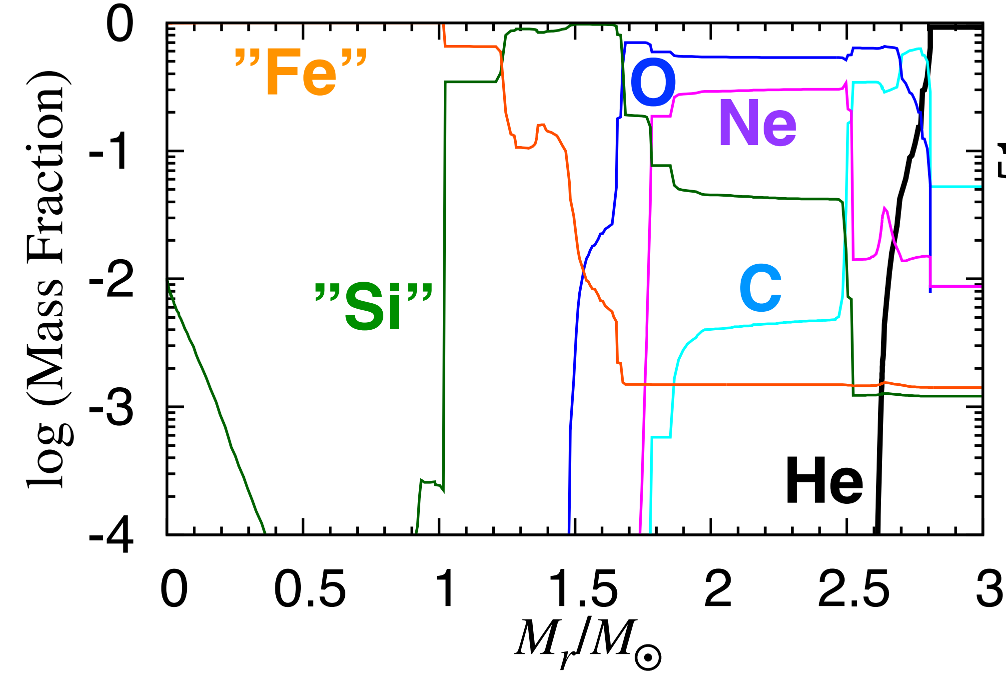


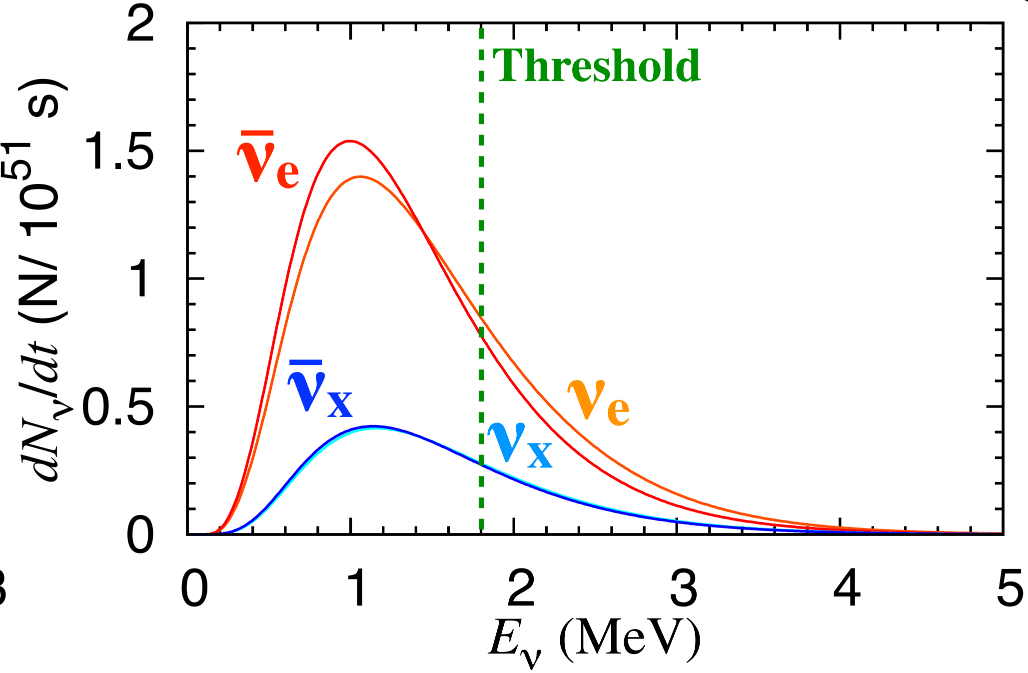
- **15 $M_\odot$ star (1.15 days)**

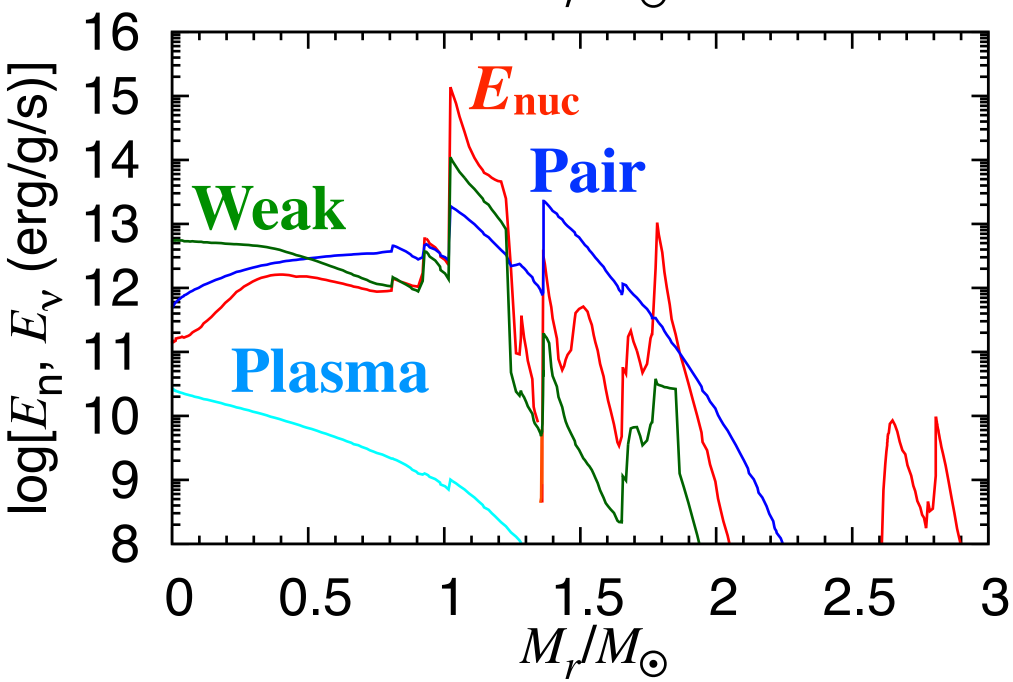
  $M_{Fe} = 1.49 M_\odot$, $M_{CO} = 2.74 M_\odot$

  $\log T_C = 9.56$, $\log \rho_C = 7.72$

Neutrinos in Shell Si-Burning





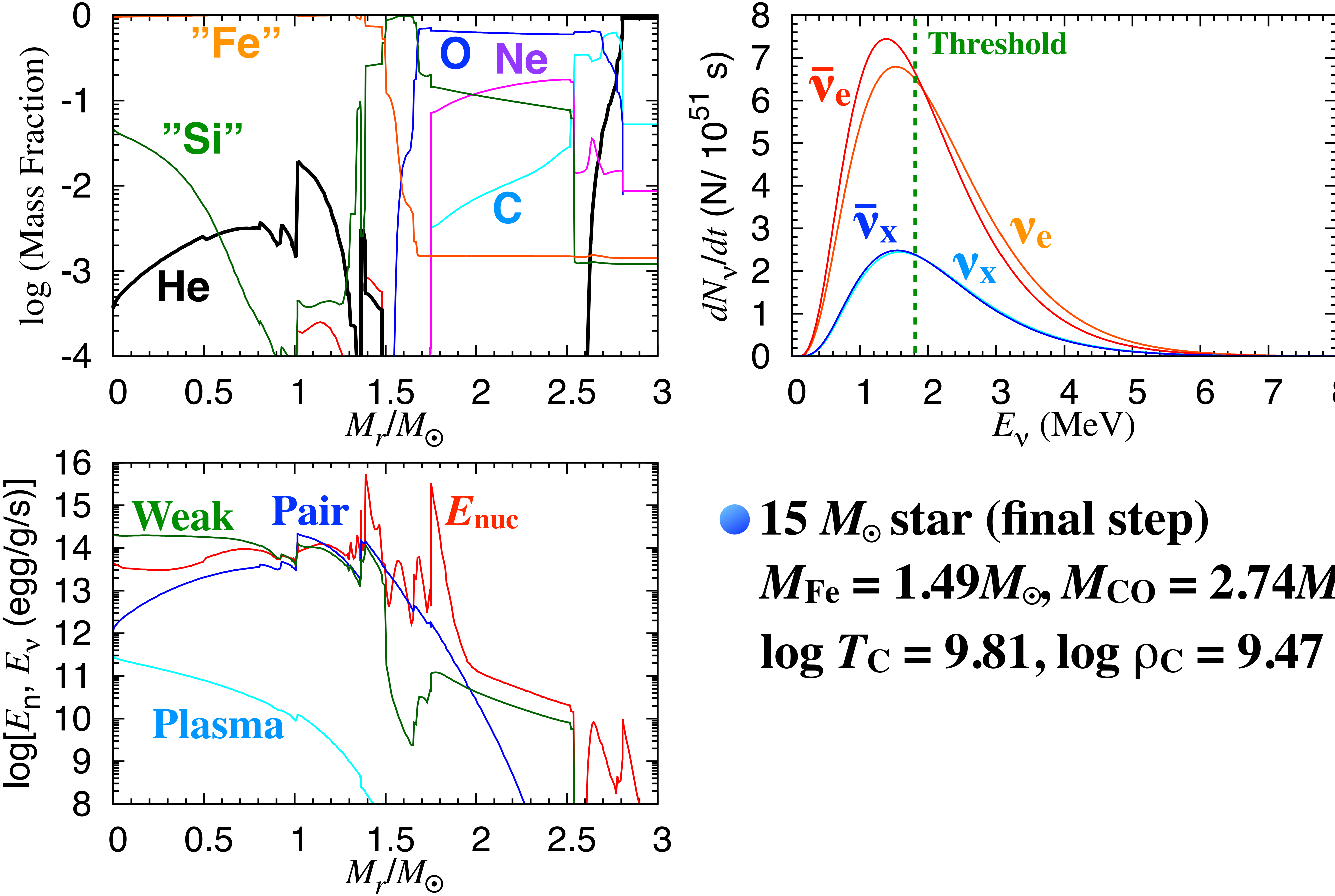


- **15 $M_\odot$ star (56.5 min.)**

  $M_{Fe} = 1.49 M_\odot$, $M_{CO} = 2.74 M_\odot$

  $\log T_C = 9.67$, $\log \rho_C = 8.85$

Neutrinos in Core-Collapse Phase



- **15 $M_\odot$ star (final step)**

$M_{Fe} = 1.49 M_\odot$, $M_{CO} = 2.74 M_\odot$

$\log T_C = 9.81$, $\log \rho_C = 9.47$

Neutrino Events by KamLAND

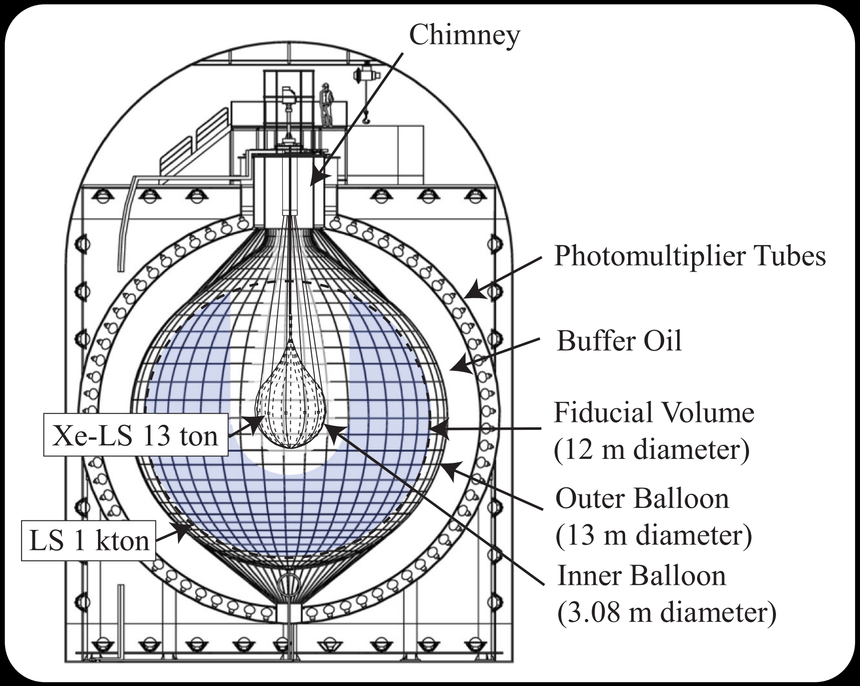
- $\bar{\nu}_e$ detection by KamLAND

$$p + \bar{\nu}_e \rightarrow n + e^+$$

$$n + p \rightarrow d + \gamma \text{ (tagging)}$$

- $\bar{\nu}_e$ event rate

$$\frac{dN_\nu}{dt} = \frac{N_\mathrm{p}}{4\pi d^2} \int \{P_{ee}\, \lambda_{\nu e}(E_\nu) + (1\text{-}P_{ee})\, \lambda_{\nu x}(E_\nu)\} \sigma(E_\nu)\, dE_\nu$$



(Gando et al. 2013)

$N_\mathrm{p} = 5.98\times10^{31}$ (Gando et al. 2013)

d = 200 pc : distance to Betelgeuse

P_{ee}: Transition probability of $\bar{\nu}_e \rightarrow \bar{\nu}_e$

P_{ee} = 1 for no mixing

P_{ee} = 0.68 for normal

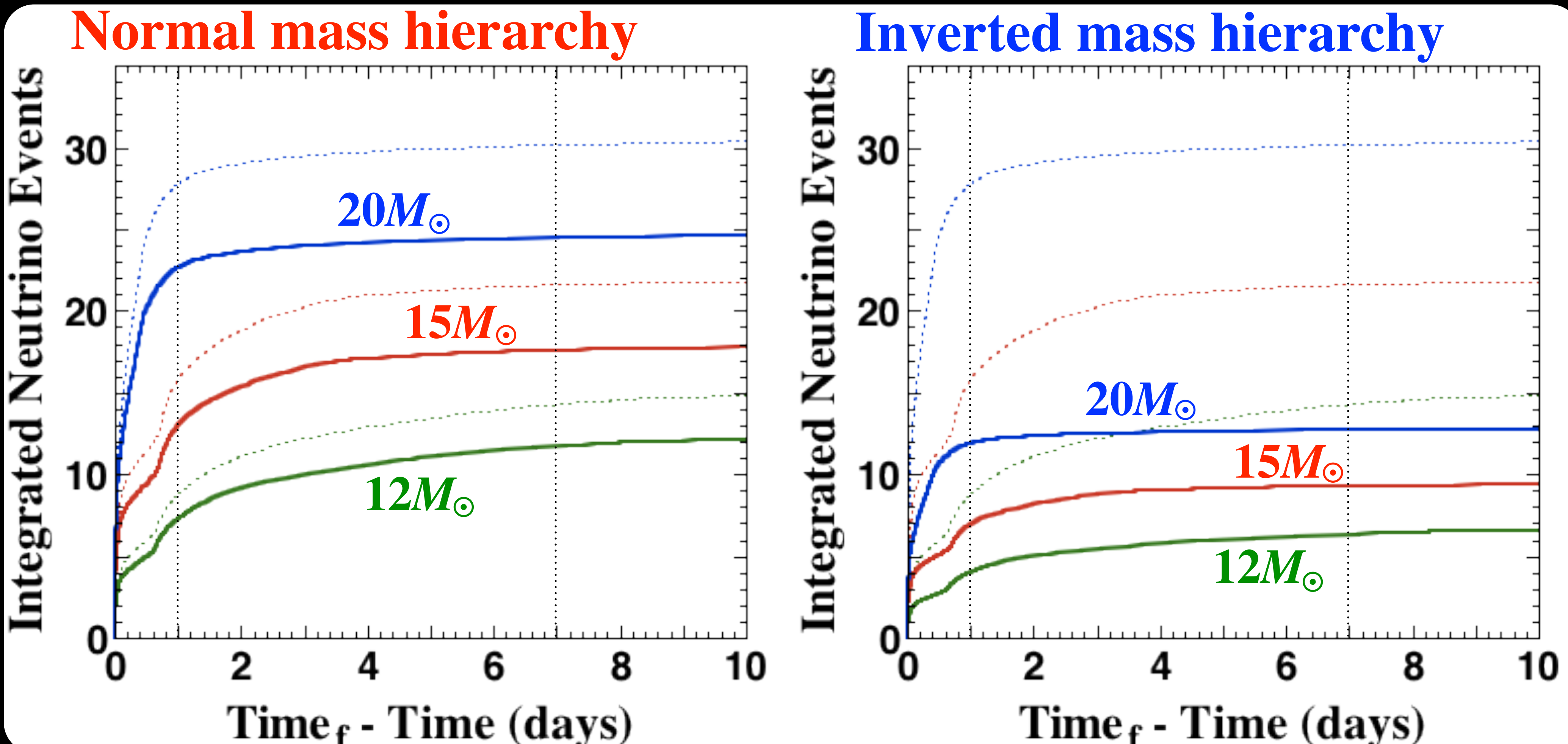
P_{ee} = 0.02 inverted

$\sigma(E_\nu)$: neutrino reaction cross section

(Strumia & Vissani 2003)

Neutrino Events of SN Progenitor

- Neutrino events from an SN progenitor at d = 200pc
  Detection by KamLAND ($p + \bar{\nu}_e \rightarrow n + e^+$)

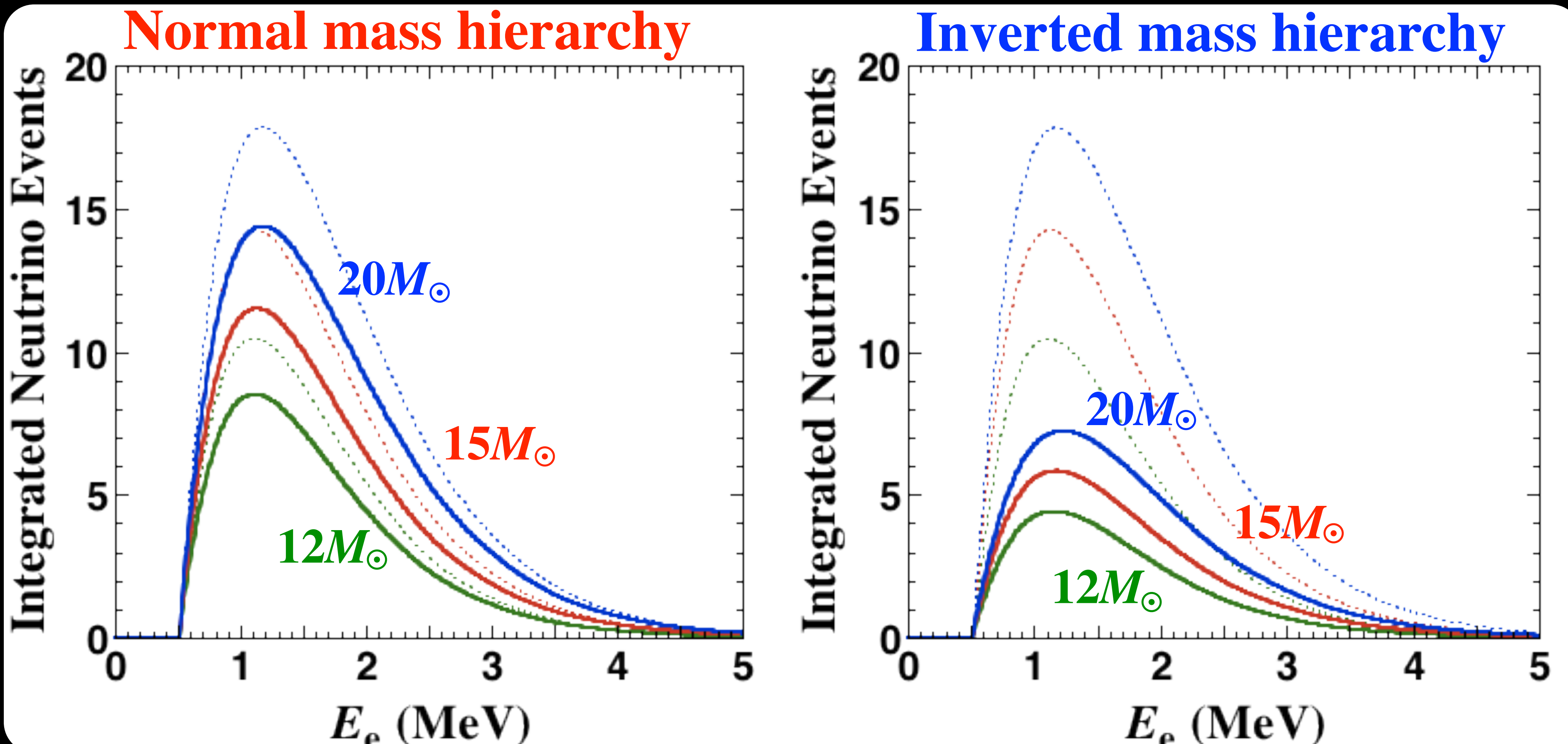


- Neutrino events in one week
  → ~ 12, 18, 24 (normal), ~ 6, 9, 13 (inverted)

Neutrino Events of SN Progenitor

- **Detected spectrum of emitted positrons**

  Detection by KamLAND ($p + \bar{\nu}_e \rightarrow n + e^+$)



- **Peak energy** → ~1 MeV

Discussion

- **Fiducial volume**
  - **JUNO, RENO-50** → **~20 × KamLAND**

    → **Number of $\bar{\nu}_e$ events is also ~20 times larger.**

- **Distance to the progenitor**
  - $d = 197.2 \pm 44.9$ **pc for Betelgeuse** (Harper et al. 2008)
    - $d \sim 150$ pc → $M \sim 15 M_\odot$, $N_{\bar{\nu}e} \sim 32$ (normal), ~ 16 (inverted)
    - $d \sim 250$ pc → $M \sim 20 M_\odot$, $N_{\bar{\nu}e} \sim 16$ (normal), ~ 8 (inverted)

Summary

- Neutrinos from the progenitor of a nearby SN before SN explosion are detectable by KamLAND.
  - → Tens neutrino events from a SN @ a few 100 pc in a few days ~ one week

- 12, 15, and 20 $M_\odot$ models @200pc (distance to Betelgeuse)
  - → $\bar{\nu}_e + p \to n + e^+$

    $N_{\bar{\nu}e}$ ~ 12, 18, and 24 (normal), ~ 6, 9, and 13 (inverted) in a week before SN explosion

- Prospects
  - → Investigation of the dependence of the emission rates and spectra of neutrinos on stellar interior
  - → Prediction of the neutrino events by other neutrino detectors such as SK, HK, JUNO, RENO-50, DUNE

Candidates of Nearby Supernovae

- Candidates of nearby supernovae

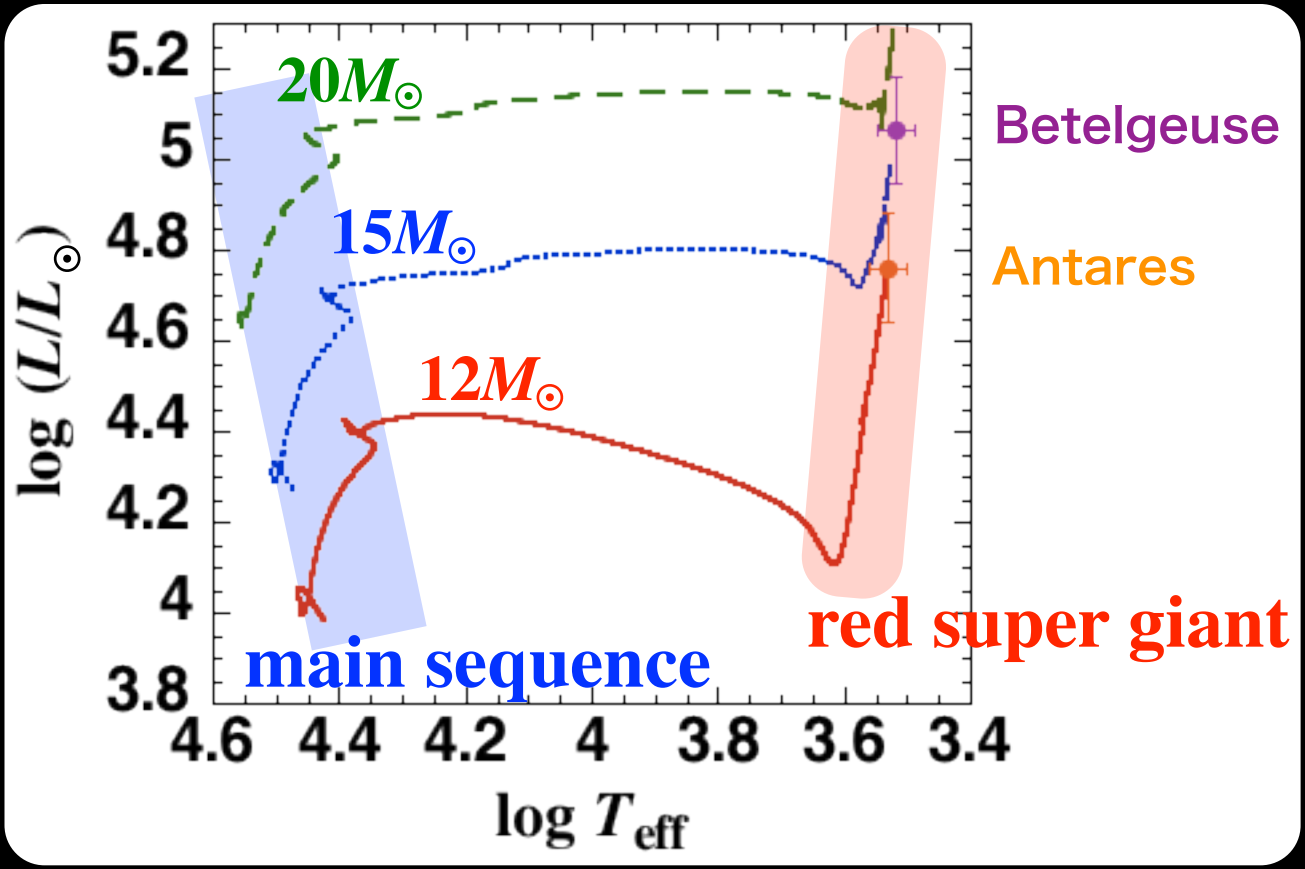
  → Red supergiants and Wolf-Rayet stars within the distance of *a few 100* pc

  - Betelgeuse (α-Ori) ... ~15-17$M_\odot$, d = 197.2±44.9pc (Harper et al. 2008)
  - Antares (α-Sco) ... ~12$M_\odot$, d = 180pc ±15% (Schröder & Cunz 2007)
  - γ Velorum ... ~10$M_\odot$ Wolf-Rayet star, d = 336±8pc (North et al. 2007)

- Possibility of the detection of low-energy neutrinos from an SN progenitor *before* SN explosion

Stellar Evolution on Stellar Surface

- Diagram on effective temperature - luminosity plane



$d = 197.2 \pm 44.9$pc
(Harper et al. 2008)

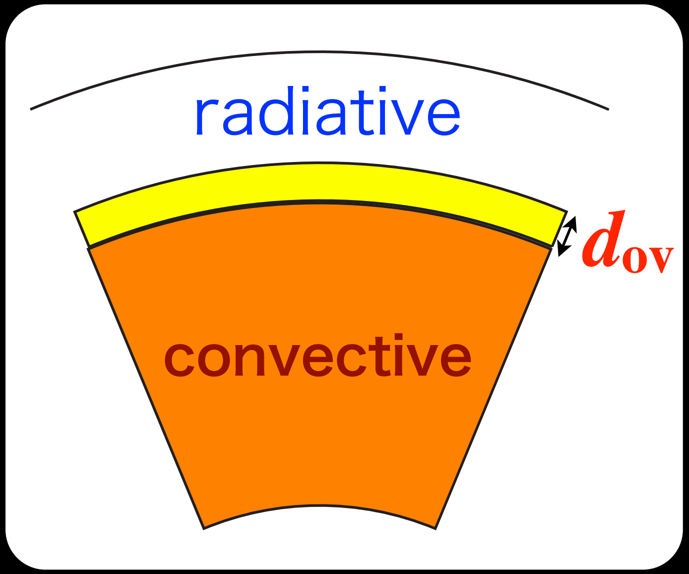
$d = 180$pc $\pm 15\%$
(Schröder & Cunz 2007)

- More massive star is more luminous.
- Massive stars evolve to red super giants after core H-burning.

Convective Region in Stellar Interior

Treatment of convection in 1D stellar evolution models

- Convectively unstable with the change of chemical composition
  → Convection



- Convective boundary

  $v_{conv} \fallingdotseq 0$ at the boundary

  → overshooting
  (extended convective region)

  overshooting region: $d_{ov} = \alpha_{ov} H_p$

  α_{ov}: parameter

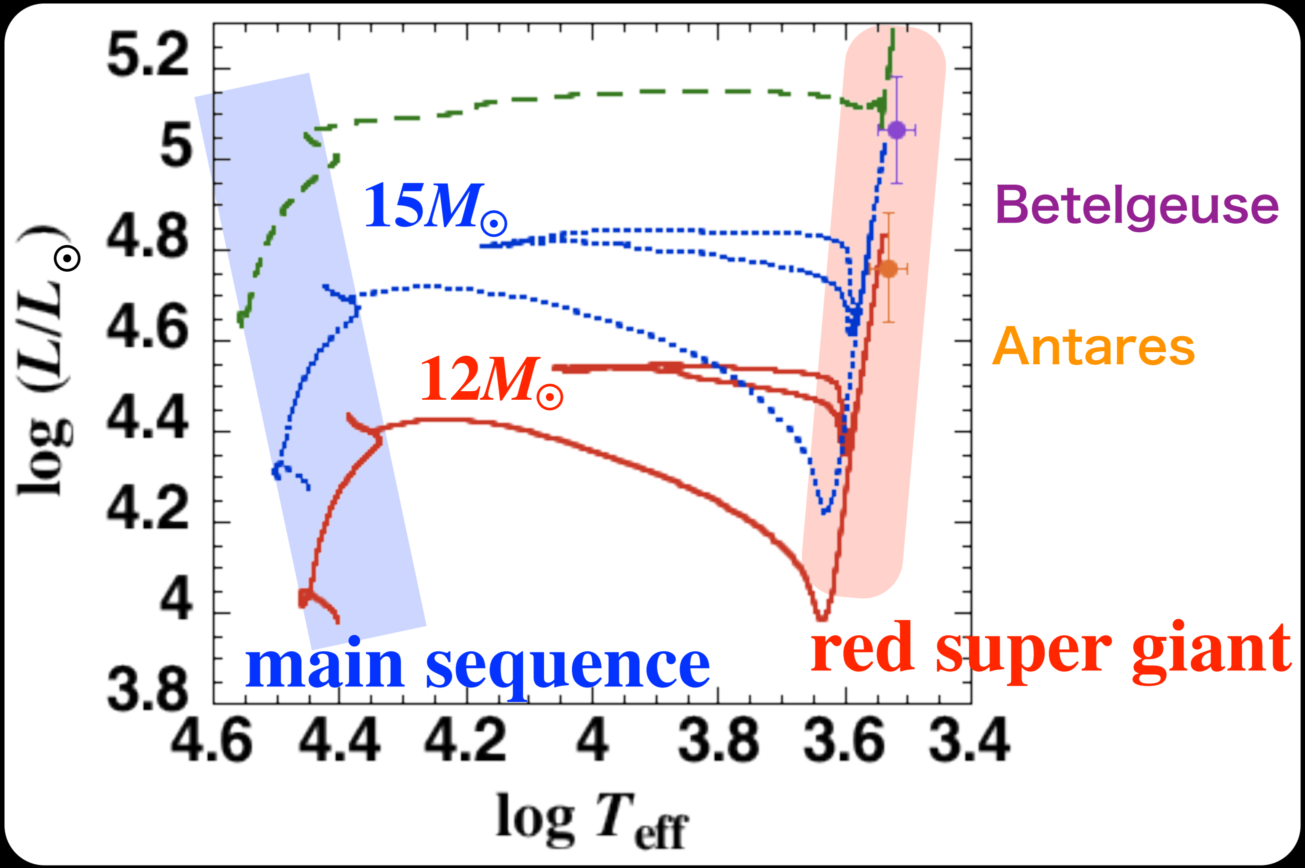
- Large overshooting

  → Large CO core

Stellar Evolution on Stellar Surface

- Diagram on effective temperature - luminosity plane

Models adopted in Kato et al.



$d = 197.2 \pm 44.9$pc
(Harper et al. 2008)

$d = 180$pc $\pm 15\%$
(Schröder & Cunz 2007)

- Larger overshoot parameter

→ More luminous star with larger CO core

Advanced Evolution of Massive Stars

- Period and number of neutrino events depend on stellar mass.

Models in this study

M / $M_\odot$	M_{CO}	M_{Fe}	$t_{Si\text{-}b}$ (d)
12	1.82	1.28	8.6
15	2.74	1.49	4.4
20	4.64	1.44	1.1

Models in Kato et al. (2015)

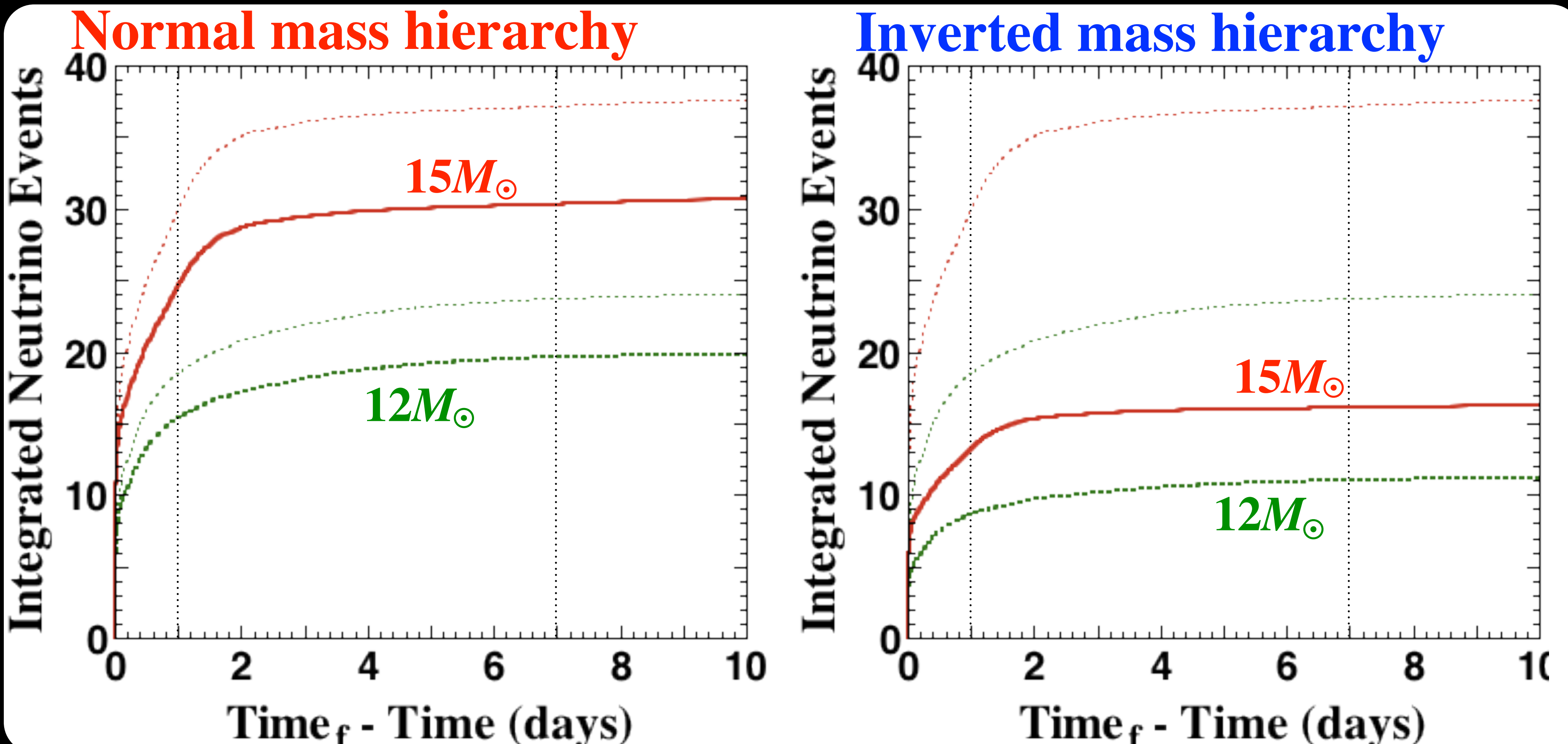
M / $M_\odot$	M_{CO}	M_{Fe}	$t_{Si\text{-}b}$ (d)
8.4	1.37	-	-
12	2.22	1.44	4.9
15	3.26	1.51	2.4

- Observation of neutrinos from an SN progenitor

  → Information of the innermost region of the star

Neutrino Events of SN Progenitor

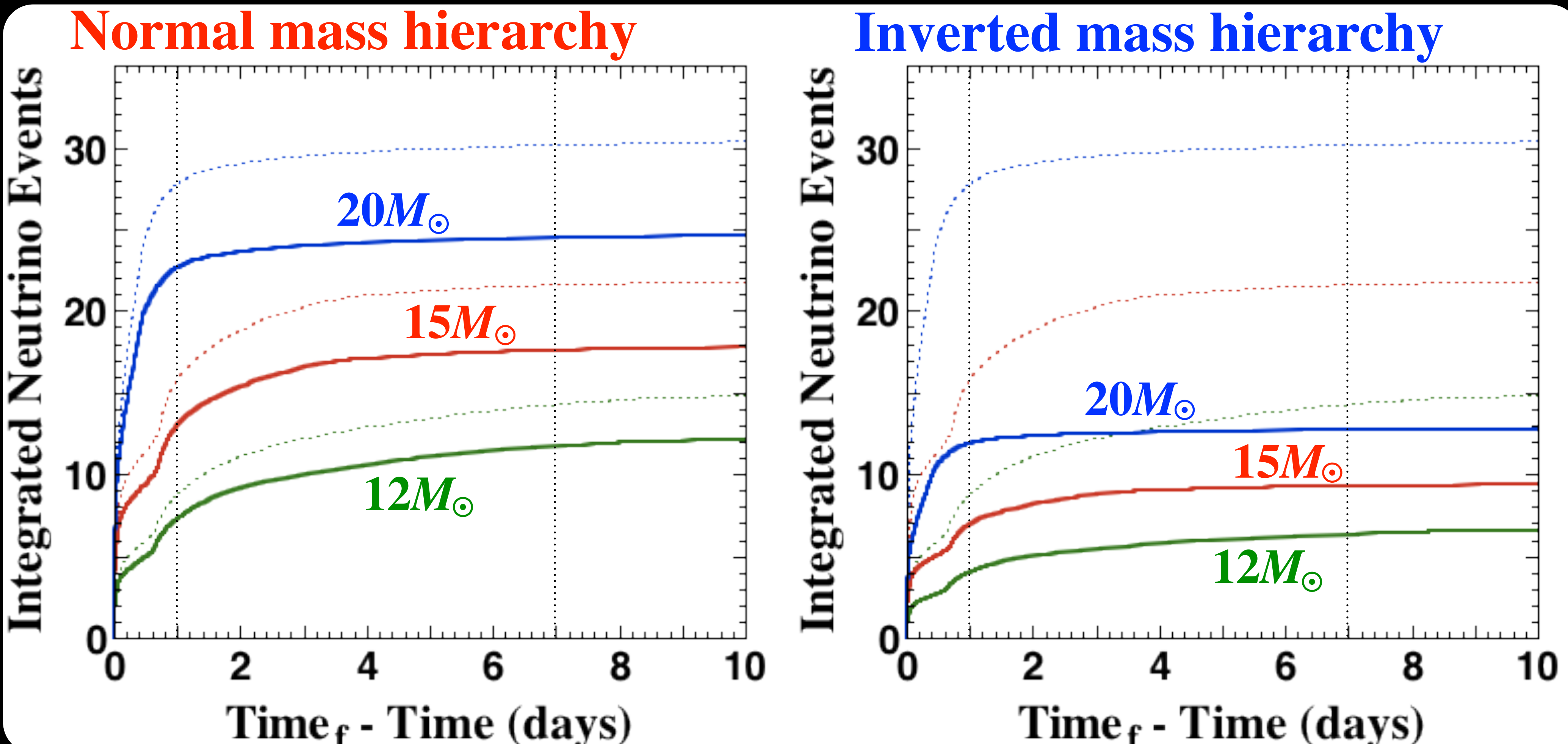
- Neutrino events using models in **Kato et al.** at d = 200pc
  Detection by KamLAND ($p + \bar{\nu}_e \rightarrow n + e^+$)



- Neutrino events in one week
  → ~ 20, 30 (normal), ~ 11, 16 (inverted)

Neutrino Events of SN Progenitor

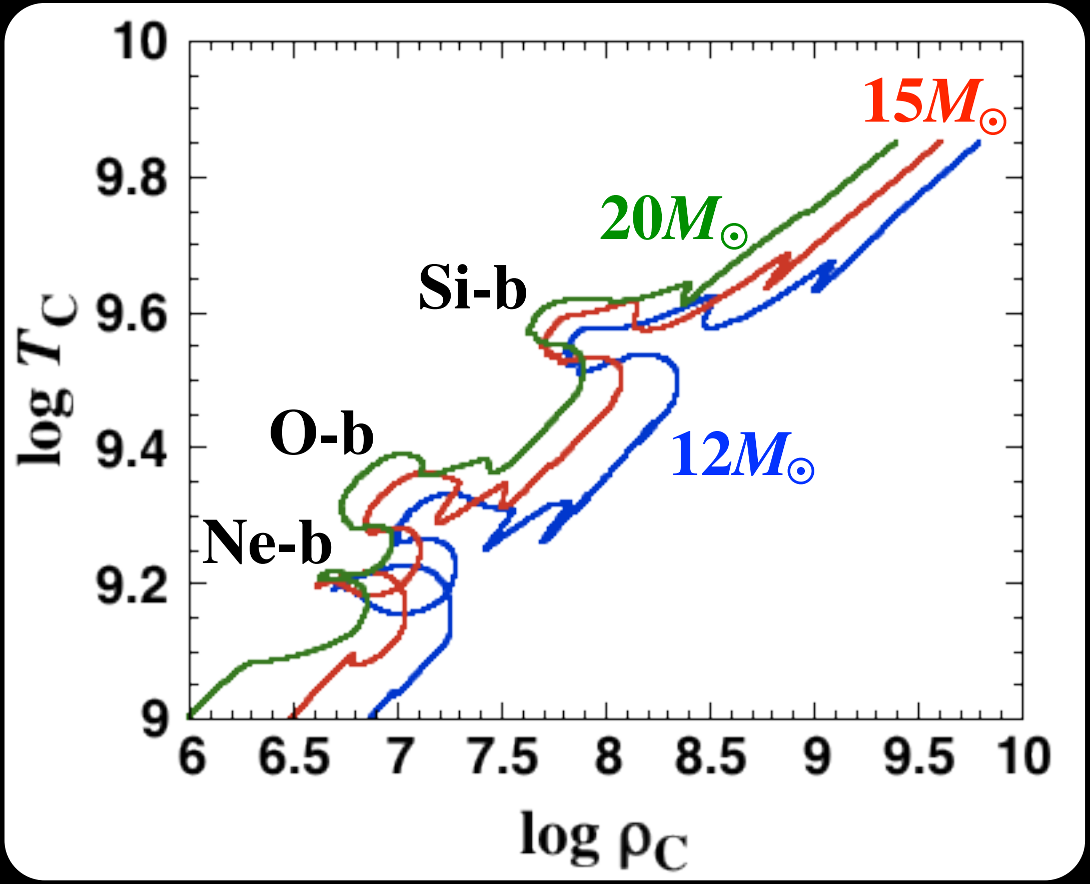
- Neutrino events from SN progenitor at $d = 200$pc
  Detection by KamLAND ($p + \bar{\nu}_e \rightarrow n + e^+$)



- Neutrino events in one week
  → ~ 12, 18, 24 (normal), ~ 6, 9, 13 (inverted)

Advanced Evolution of Massive Stars

- Period and number of neutrino events depend on stellar mass.



- Period from Si-burning to core-collapse

12$M_\odot$: 8.6 days
15$M_\odot$: 4.4 days
20$M_\odot$: 1.1 days

- Observation of neutrinos from an SN progenitor
  → Information of the innermost region of the star

Neutrino Events by KamLAND

- $\bar{\nu}_e$ detection by KamLAND

  $p + \bar{\nu}_e \rightarrow n + e^+$

  Low energy threshold by *neutron* tagging

  $E_{\mathrm{threshold}} = 1.8$ MeV

- $\bar{\nu}_e$ event rate

$$\frac{dN_\nu}{dt} = \frac{N_\mathrm{p}}{4\pi d^2} \int \{P_{ee}\, \lambda_{\nu e}(E_\nu) + (1\text{-}P_{ee})\, \lambda_{\nu x}(E_\nu)\} \sigma(E_\nu)\, dE_\nu$$

$N_\mathrm{p} = 5.98\times10^{31}$ (Gando et al. 2013)

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$P_{ee} = 0.68$ for normal

$P_{ee} = 0.02$ inverted

$\sigma(E_\nu)$: neutrino cross section (Strumia & Vissani 2003)

Massive Star Evolution Model

- **Massive star evolution model**

  (e.g., Yoshida & Umeda 2011; Umeda, Yoshida, Takahashi 2012; Takahashi, Yoshida, Umeda 2013; Yoshida, Okita, Umeda 2014; Takahashi, Umeda, Yoshida 2014; Takahashi et al. 2015)

$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2} \qquad \frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial \ln T}{\partial \ln P} = \min(\nabla_{\mathrm{ad}}, \nabla_{\mathrm{rad}}) \qquad \frac{\partial L_r}{\partial M_r} = \varepsilon_{\mathrm{nucl}} - \varepsilon_{\nu} + \varepsilon_{\mathrm{grav}}$$

- **Nucleosynthesis and energy generation**

  ➡ **Reaction network of 300 nuclei (*n*, H - Br)**

  Diffusive mixing of chemical composition

- **Ledoux criterion for convection**

  Semiconvection and overshooting are taken.

- **Mass loss**

  Rate: Vink et al. (2001); Nieuwenhuijzen & de Jager (1990)